A discussion of the risks and benefits of using rock terracing to limit soil erosion in Guizhou Province

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Abstract: The construction of stone terraces to minimise soil erosion is common throughout Guizhou. This technique, however, has high inherent risk. Stone terraces are usually much higher than those with earth risers. While they trap a greater thickness of soil on the slope they increase the risk of slope failures, reduce moisture and nutrient availability to plants, and thin more soil up slope. The stone risers also threaten long-term productivity. When a riser collapses debris is deposited over the terrace below making farming difficult. These breaches in the terrace focus surface runoff leading to gully formation and increased sediment transport down slope. Artificial drainage systems, often used in conjunction with terracing, compound the risk. These channels prevent precipitation from soaking into the soil. This limits groundwater and soil moisture recharge which reduces the availability of water for crops and the length of the growing season. The rapid drainage of water from the slope reduces the time of concentration of the catchment resulting in an increase in flood activity. Floods are caused by smaller rainstorm events. They arrive faster and peak quicker and higher than before the channels were constructed. Engineering solutions to soil erosion must therefore be used in conjunction with, and are not as a substitute for, good land management strategies. Furthermore, despite changes in land use practices, and the application of new technologies, there is a maximum amount of production that can be obtained from this land on a sustainable basis.

Keywords: Soil erosion; Reafforestation; Terracing; Sustainability; Landsliding; Environmental management

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Introduction

Although Guizhou's agricultural resources are potentially good i.e., the province has a moist sub-tropical climate (annual rainfall is between 1 100 and 1 300 mm), is underlain by limestone bedrock, and soil covers approximately 90% of the province's total area; in terms of agricultural production soil resources are insufficient. Guizhou is dominated by mountainous (62% of total area) and hilly (31% of total area) terrain with very little flat land. Only 147,500 km^2 of Guizhou's soil resource (approximately 84% of total land area) is available for agriculture, forestry, and livestock husbandry. By the end of 1998, forested land covered 31% of the province, while the actual cultivated land area totalled only 1.8 million hm^2 (10.5% of total area). As a result the per capita possession of cultivated land was only 0.05 hm^2 (corresponding to a man/land ratio of 20/hm^2 of cultivated land). This is well below the national average and 60% less than in 1949 (Guizhou People's Government). In addition to being small in area, the cultivated land of Guizhou is also of poor quality. Only 42% of cultivated land within the province is irrigated. First grade land, with thick, fertile soil and good irrigation is, as a result, extremely limited.

Guizhou is one of the poorer provinces in China. The average income per rural resident in 1998 was 1865 Yuan, approximately 60% of the national rural average and only 34% of the national urban average. Furthermore, 38% of its counties are below the official poverty line. The economy of Guizhou relies heavily on agriculture i.e., 86% of the work force is engaged in agriculture (Guizhou People's Government). Rapid population growth (between 1997 and 1998 Guizhou had a natural growth rate of approximately 500 000 or 14%) and past land use decisions, largely in response to this rapid growth (i.e., rural and urban construction projects and cropland conversion into forest plantations which reduce the amount of land available for cultivation) are placing increased stress on an already limited soil resource (Ash and Edmonds 1998; Guizhou People's Government; Hill 1993). Soil erosion caused by human activity, for example, is increasing and becoming more severe. Approximately 44% of Guizhou Province is now affected by soil erosion, half of which is moderate to very severe. This makes it one of the most severely affected provinces in China. Average erosion rates have been estimated at 3 950 t·km^{-2}·a^{-1} for the Changjiang River catchment and 2 970 t·km^{-2}·a^{-1} for the Zhujiang River catchment, corresponding to 80% and 19% respectively of the total volume of eroded soil for the province (Zhang 1999) This environmental degradation has placed additional stress on the people of Guizhou and severely limits sustainable economic development opportunities.

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Sheet erosion and the development of rills and gullies caused by surface runoff are ongoing and increasing problems throughout Guizhou. However, the risk from land sliding during extreme rainfall events is also a significant erosion problem (Li 1989). Qingzhen, Zhijin, and Nayong counties (Fig. 1), with a total area of 6 651 km^2, are particularly severely affected. Some erosion, and consequential sedimentation, is expected because of the fine-grained soils, steep slopes, and high rainfall. Natural erosion rates have, however, been accelerated by land use change and the clearance of vegetation from marginal lands. Growing population pressures since the 1950s in particular have led to an intensification of land use and the removal of vegetation cover to meet the increasing demands for cultivated land (Fig. 2). In 1998 alone over 200 000 hm^2 were newly cultivated for grain production in Guizhou. As a result, the rate of soil loss over much of the steeper terrain has increased. By 1998 approximately 65%-70% of Nayong and Zhijin counties were affected by soil erosion, approximately half of which was classed as moderate to very severe (Zhang 1999). Average erosion rates have been estimated at 6745 t/km^2, equivalent to a surface lowering of approximately 2.5 mm/a. Because this loss is almost entirely from the soil mantle it represents a major reduction in potential productivity. In fact, despite bringing considerable amounts of marginal land into cultivation during the last decade, and significant increases in technical inputs, Guizhou has reported stagnant grain production. The loss in productivity has been attributed to the increasing degradation of agricultural land (Rozelle *et al.* 1997). Soil erosion, however, is not a problem restricted to the hillslopes. High sediment loads in rivers, for example, have rendered over half the power stations in these counties inoperable and increased the flood frequency.

Fig. 1 The location of Qingzhen, Zhijin, and Nayong counties in Guizhou Province.

The problems caused by increased soil erosion include: reduced productivity via soil loss from hillslopes, deposition of detritus on lower slopes and valley floors, nutrient loss, reduced rooting zone depth, reduced organic matter and water holding capacity, and changes in soil structure and clay content; adverse changes to the hydrologic regime of the hillslopes and rivers e.g. an increase in flood frequency; increased landslides or debris flows; and the reduced efficiency and capacity, and increased maintenance costs, of hydraulic structures because of high sediment loads. Although erosion and mass wasting processes are a natural part of any landscape and must be considered in any land management strategy, human influence (i.e., agricultural and industrial development) has dramatically accelerated erosion rates in Guizhou Province. Soil erosion restricts agricultural production, creating a downward spiral of land degradation and yield losses (Zhang 1999).

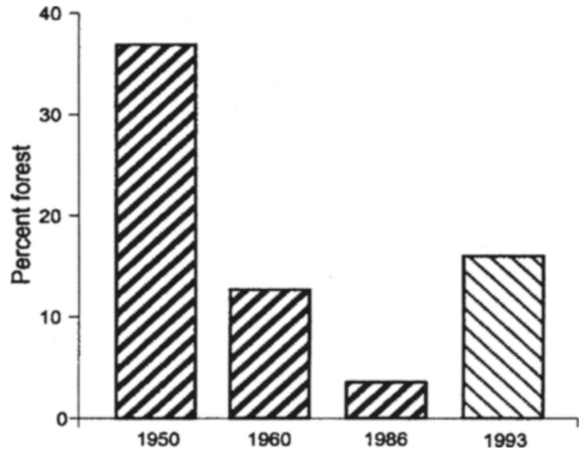

Fig. 2 Forest removal from Zhijin and Nayong counties since the 1950s has been dramatic. The increase in forest cover more recently reflects potential reafforestation under the World Food Program China Project 3356 ("Giving Hope").

The problem

Soil erosion is a significant problem throughout Guizhou but particularly in Qingzhen, Zhijin, and Nayong counties. The wide valley floors composed of detrital sediment, and the shape of valley slope profiles which dip deeply beneath the current floor of the valleys, are evidence that erosional and depositional processes are natural. In fact, if these processes had not operated in the past there would be very little highly productive paddy land in the area. There is also little doubt, however, that the rates of these processes have accelerated in recent years, much to the detriment of local communities.

The soils in this area are fine-grained, non-cohesive, and contain few aggregates. Excessive tillage, repeated burning, increases in soil temperature, and the continual harvesting of most vegetative matter have resulted in the soils having a very low organic content (Guizhou People's Government; Zhang 1999). Numerous studies have shown that organic content is important in maintaining aggregate stability i.e., resistance to erosion by rainfall or runoff, and nutrient

availability particularly on cultivated soils (Chenu *et al.* 2000; Guerra 1994; Luk 1979; Shepherd *et al.*, 2001; Watts and Dexter 1997; Young *et al.* 1982). The lack of organic matter means that the soil acts as a collection of small discrete particles, which are easily transported by surface runoff. An increase in organic matter would improve the soil structure, increase aggregate size, and increase the hydraulic conductivity and permeability thereby reducing runoff. It would also help to stabilise seasonal moisture fluctuations and increase the length of the growing season.

Erosion has accelerated because of the clearance of vegetation and increased utilisation of marginal lands (Hill 1993; Shi and Li 1999). The marginal nature of this land for sustaining production is shown by the fact that it quickly reverts to scrub if maintenance is not ongoing. This land was brought into production in response to continuing population growth and a reduction in the long-term productivity of traditional agricultural lands.

Deforestation and the clearance of land for cropping has exposed large areas of these easily erodible soils, often on relatively steep slopes (>30°), to the effects of rainstorm events and increased surface runoff. This, combined with increases in soil temperature, reduced organic content, the breakdown of the soil structure, seasonal rainfall (and high intensity rainstorm events), soil compaction, and inappropriate land tillage practices has led to the high erosion and sediment transport rates.

While soil erosion from sheet erosion, and rill and gully development are the most obvious response to this land clearance the impact of high intensity rainstorms, triggering rapid shallow landslides, is also significant (Li 1989). The periodicity of rainstorms (either long enough or intense enough) to trigger rapid landsliding, the fact that many of the slopes have only recently been cleared (therefore the roots are still having some effect), and the shallow nature of the soils mean that the full impact of this form of mass movement may take decades to become apparent.

The rates of soil erosion are highly variable, both spatially and temporally. Soil loss around harvest and planting times, especially when they coincide with rainstorm events, is significantly higher than at other times of the year when vegetation cover is maintained. Soil erosion causes a redistribution of soil on the slope. Soils tend to thin on the upper slopes and thicken further down the profile. Often, sediment eroded from the valley sides is deposited on top of intensively cultivated land on the valley floor (Zhang 1999). Where this sediment is composed of coarse particles it dramatically reduces productivity from what was the most fertile land.

The re-establishment of a full vegetation cover on these slopes would reduce soil erosion by runoff to very low levels, and landsliding except under more extreme climatic events. In many situations, however, this is not practical because the population pressures that led to the use of this land restrict its conversion back to what is seen as non-productive use, even with some form of compensation. A compromise is therefore necessary which allows the utilisation of the land on a sustainable basis while reducing soil loss.

Existing land management practices are mining the soil resource for short-term gain. This is likely to lead to greater levels of social distress and costs in the future when the higher expectations and living standards can no longer be sustained. While the use of chemical fertilisers may provide a buffer against the loss of natural soil fertility this approach is inefficient and not viable on these slopes in the long term.

Reafforestation of entire catchments is not practical for a number of social, cultural, ethnic, and historic reasons. Even in situations where production from the steeper land is so low that losses through reafforestation would be minimal this is the only land available to many families. In this case reafforestation of the upper slopes simply causes clearance of adjacent land, often with an increase in soil erosion. This is because the newly cleared land has lower productivity (which is why it was not cleared earlier) so more is required. This generates more erosion. What is required therefore is a strategy which reafforests the less stable slopes while increasing production from other areas, through either new technology or crops, to compensate for the loss of land.

An integrated land use system is required which allows the identification of those areas which must be reafforested, using a flexible range of agro-forestry options, and those that can be used for sustainable cropping. Since the principal erosion processes are currently caused by surface runoff, the use of grass species and improved grassland offer benefits to both land management and livestock farming. While traditional practices are appropriate in some areas, particularly those with a long land use history, this is not always the case.

Current solution

Terracing, a common soil conservation technique used on cultivated fields (Gebremedhin *et al.*, 1999), has been extensively adopted throughout Guizhou's steeper terrain, usually with rock risers. While terracing is essential for rice cultivation, to manage the water within the paddy, this is not the case on these steeper slopes. On steeper slopes terracing is used to reduce the slope angle, to slow down and reduce runoff, to increase infiltration, and subsequently decrease soil erosion by surface runoff. Obviously terracing achieves these aims to varying degrees but it has several negative consequences as well. This is because the terraces act as debris dams, storing sediment eroded from up slope (Table 1).

Some of the effects of terracing used in this manner include:

1. A reduction in potentially productive land i.e., the terrace riser (Fig. 3). This may be partly offset by an increase in production from the flatter land created but there is still an overall loss of potentially productive surface. The amount of reduction is a function of the original slope angle; terracing

of steeper slopes resulting in a greater loss of land.

2. An increase in the area of over-steepened land, in the form of terrace risers. This increase is again a function of the original slope angle, but as the area increases so does the erosion potential of this surface unless it is protected in some manner (Fig. 4).

Table 1. Changes in various attributes as a result of terracing slopes.

Slope angle (°)	Original land surface (m^2)	Flat land generated (m^2)	Reduction in usable land (%)	Steep riser generated (m^2)	Increase in usable land if riser used (%)	Soil depth against terrace riser (m)
5.0	10.0	9.96	0.4	0.87	8.7	0.87
10.0	10.0	9.85	1.5	1.74	17.7	1.74
20.0	10.0	9.40	6.0	3.42	36.4	3.42
30.0	10.0	8.66	13.4	5.00	57.7	5.00

This analysis assumes a slope 10m long and 1m wide terraced to produce a flat surface. In many situations the field produced is not horizontal and therefore these data represent an extreme scenario.

Fig. 3 Earth risers provide an increased surface area of over-steepened bare earth reducing potential productivity.

Fig. 4 Throughout large areas stone risers are used to provide protection from runoff and soil erosion.

3. Higher, or more frequent, risers as the land becomes steeper. Therefore the amount of land lost in the form of risers increases while the usable surface area decreases.

4. The trapping of large amounts of soil behind the risers. It is certainly better that soil being moved by runoff processes is stored on the slope rather than being washed into the streams and rivers. However, a soil several metres deep produces no more than a soil only deep enough to accommodate the roots. The thinner soils up slope will have a lower production because of a reduced moisture and nutrient holding capacity. In terms of efficiency, it is therefore better to have the soil distributed evenly over the slope.

5. The thickened wedge of soil trapped behind the terrace riser has several additional disadvantages and management implications. First, any precipitation drains rapidly past the root zone to where it can no longer support plant growth. Second, the hydrostatic head generated by this water, if the terrace is not free draining, may lead to the failure of the terrace. Third, the flatter slope and improved drainage characteristics of the soil can create higher pore water pressures, particularly during intense rainstorms. These reduce the shear strength of the soil and consequently increase the potential for rapid landsliding by reducing the Factor of Safety (see Equation 1).

$$FS = \frac{\text{Shear strength}}{\text{Shear stress}} = \frac{c + (\gamma_{sat} - m.\gamma_w) \cdot z \cdot \cos^2 \beta . \tan \phi}{\gamma_{sat} . z \cdot \sin \beta \cdot \cos \beta} \qquad (1)$$

Where: c is soil cohesion,. γ_{sat} is saturated density of soil, γ_w is density of water, m is ratio of saturated thickness to total thickness of soil, β= slope angle, ϕ is angle of internal friction of the soil, z is soil thickness.

·Fourth, the natural soil thickness on many of the slopes is below the critical value (Z_c) for shallow planar landsliding (see Equation 2). For example, soils less than 1m thick seldom fail by this mechanism.

$$Z_c = \frac{\dfrac{c \cdot \sec^2 \beta}{\gamma_{sat}}}{\tan \beta - \dfrac{(\gamma_{sat} - \gamma_w)}{\gamma_{sat}} . \tan \phi} \qquad (2)$$

The trapping of soil behind the riser, however, may allow the soil thickness to exceed this critical value and landslid-

ing may result during intense rainstorms. Therefore, while terracing reduces erosion from surface runoff it may actually increase the risk from, and probability of, shallow landslides and large scale soil loss during intense rainstorms.

Terracing can help to limit soil erosion on some slopes, in some areas, but its effect on the soil resource must be clearly recognized. It is essential to find some management strategy, which allows production from the risers as these are currently a waste of usable land. It is also better to construct a number of small terraces than a single large one. This reduces the risk of failure and helps maintain an even distribution of soil over the slope.

Stone terraces

The construction of a stone riser reduces erosion of the face of the terrace (Gebremedhin *et al.* 1999) but it also poses inherent risks. Stone terraces are usually much higher than those with simple earth risers. They therefore trap a greater thickness of soil on the slope: increasing the risk of slope failures, reducing moisture and nutrient availability to plants, and thinning the soil further up slope. The stone risers also threaten long-term productivity. Should a riser collapse, and failures are common, then coarse debris is deposited over the terrace below (Fig. 5). This reduces the productivity, and increases the difficulties associated with production on the lower terrace. These breaches also act as a channel for surface runoff leading to additional problems of runoff control and increased sediment transport down slope.

Fig. 5 Most stone risers contain at least one breach. These breaches concentrate runoff leading to scouring both up and down slope and the deposition of coarse rock debris over the productive land below.

Stone terracing is usually undertaken in conjunction with the artificial control of runoff (Fig. 6). The control structures and channels are very steep and paved with stone to improve their hydraulic efficiency. Consequently, when water flows in these channels it has a high velocity and resultant energy. There are several potential problems with the use of these drainage channels. They collect water from the slope and drain it rapidly to lower levels. This reduces the opportunity for the water to soak into the soil, limiting groundwater and soil moisture recharge, which in turn reduces the supply of water for crops and shortens the growing season. The rapid drainage of water from the slopes also reduces the time of concentration of the catchment resulting in an increase in flood activity. Floods are now caused by smaller rainstorm events. They arrive faster and peak quicker and higher than before the channels were constructed.

These channels are designed from a very limited database and knowledge of the amount of runoff that can be expected. To save losing productive land they are therefore usually smaller than the optimum size. As a result there is a high probability that the discharge capacity of the channels will be exceeded with the water escaping. When this happens the high velocity and volume of flow mean that damage will be extreme.

Fig. 6 Stone-lined channels and causeways concentrate and accelerate runoff during storm events. Failure of these structures and the uncontrolled release of this energy is a major risk inherent in this form of design.

In general, it is better soil conservation management to keep both the soil and water spread out evenly across the slope rather than concentrated at a few specific locations, or trapped behind large debris dams (Fig. 7). In the case of the soil, this allows good rooting depths, and therefore production, across the entire slope rather than in narrow bands on the terraces. With respect to water it allows runoff to be slowed and increased time for infiltration.

The future

A considerable investment has been made in terracing hillslopes and providing artificial drainage to minimise soil erosion (Guizhou People's Government). However, inappropriate cropping regimes on these "protected" slopes continue to promote erosion. Engineered soil conservation solutions are therefore being used as a substitute for sustainable agricultural practices that reduce runoff and soil erosion. Effective sustainable soil conservation requires a

range of techniques rather than the imposition of engineering solutions.

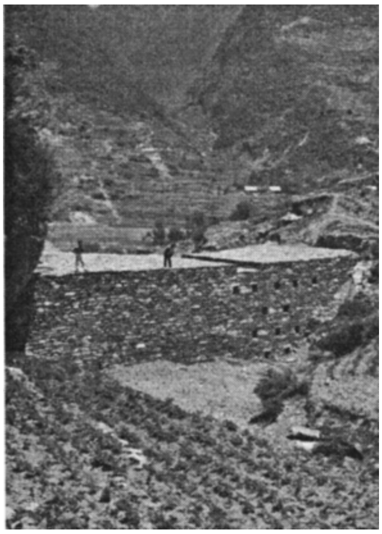

Fig. 7 A large debris dam designed to trap sediment eroded from higher on the slope. This particular dam was completely filled within eighteen months.

The landscape has been adjusting to an increase in erosion for the past 40 years. Reducing erosion on upper slopes may therefore have significant, perhaps negative and unforeseen, changes to the processes and landscape at lower levels. This may include stream incision, bank erosion, and increases in channel gradients that in turn may pose a threat to roads, bridges, and other infrastructure. These potential changes also need to be considered.

Economic development of the area requires an integrated programme that extends beyond simply agricultural development. As stated already, there is a limit to the sustainable production from this hill country, and this limit is not high. As a consequence, there are a maximum number of persons, income level, and quality of life that can be supported by agriculture alone.

Conclusions

The major land management problem in Guizhou is the sheet erosion of soils. Deforestation, and the clearing of vegetation from hill slopes for cropping, has exposed large areas of fine and easily erodible soils to the effects of rainstorms. This, combined with compaction and inappropriate land tillage practices, has led to high rates of erosion and sediment transport down slope. This has greatly reduced potential agricultural productivity.

The effect of shallow landslides on these slopes on the viability of agricultural systems and rural economies has also yet to become apparent. This is because of the low frequency of potential landslide-triggering rainstorms, and the time it takes the resistance once provided by trees to disappear through root decay. It is essential that areas at risk, such as topographic depressions and recently cleared fields, be identified so that damage and losses can be minimised.

Current land management practices that are mining the nutrients and soil are both dangerous and counter-productive. Dangerous because of the serious soil loss, and counter-productive because the short-term gains are unsustainable. The present and future social and economic consequences of such losses must be avoided.

The re-establishment of a complete vegetation cover would reduce soil erosion by surface runoff to very low levels, and landsliding except under the most extreme climatic events. This, however, is not feasible for social, cultural, ethnic, historic, and practical reasons. The pressures, which led to the intensive utilisation of marginal land, do not permit its return to what are considered non-productive uses, even with compensation. A compromise is therefore necessary which allows the utilisation of the land for productive purposes while reducing soil loss to a sustainable level.

The construction of terraces has been adopted to minimise soil erosion. This technique, particularly the use of stone terraces, however, has high inherent risk. Stone terraces are usually much higher than those with earth risers. They trap a greater thickness of soil on the slope: increasing the risk of slope failures, reducing moisture and nutrient availability to plants, and thinning the soil up slope. The stone risers also threaten long-term productivity. When a riser collapses debris is deposited over the terrace below making farming difficult. These breaches focus surface runoff leading to gully formation and increased sediment transport down slope. Artificial drainage systems, often used in conjunction with terracing, compounds the risk. These channels prevent precipitation from soaking into the soils. This limits groundwater and soil moisture recharge, which reduces the supply of water for crops and the length of the growing season. The rapid drainage of water from the slopes reduces the time of concentration of the catchment resulting in an increase in flood activity. Floods are caused by smaller rainstorm events. They arrive faster and peak quicker and higher than before the channels were constructed.

What is needed therefore is an integrated land use management system, with the watershed as the basic management unit. This would allow the identification of those areas that must be reafforested (using a flexible range of agro-forestry options) and those that can be used for sustainable cropping. Since the major erosion processes are controlled currently by surface runoff, the use of grass species and improved grassland management may provide a greater range of development options than complete reafforestation for the same degree of soil stabilisation. Such an approach would also allow a greater emphasis to be placed on livestock production.

While changes in land use practices, and the application of new technology, can lead to increases in production there

is a maximum amount of food that this land can produce on a sustainable basis. Land management practices must therefore be developed to optimise this sustainable productivity. What is the best combination of agricultural practices, techniques, crops, etc. which maximise production while minimising soil loss? Only after this question has been answered can strategies can be developed to assist in implementing this ideal.

Adopting land use practices that fail to recognise the capacity of the land to sustain productivity will create greater problems in the future while also raising false and unrealistic expectations. The goal of any agricultural development project must be the implementation of an integrated sustainable agricultural system that optimises ongoing community well-being.

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